BROOKHAVEN
NATIONAL LABORATORY

Superconducting Magnet Division

Magnet Note

Author: Arup Ghosh

Date: August 25, 2003

Topic No: 630-40 (AM-MD-330)

Topic: Superconductor R&D

Title: Critical Current Test of Nb_3Sn Cable – BNL-N-4-0010

M. Anerella
J. Cozzolino
J. Escallier
G. Ganetis
M. Garber
A. Ghosh
R. Gupta
H. Hahn
M. Harrison
J. Herrera
A. Jain
P. Joshi
S. Kahn
W. Louie
J. Muratore
S. Ozaki
B. Parker
S. Peggs
F. Pilat
S. Plate
C. Porretto
W. Sampson
J. Schmalzle
R. Soika
J. Sondericker
S. Tepikian
R. Thomas
D. Trbojevic
P. Wanderer
J. Wei
E. Willen

Critical Current Test of Nb_3Sn Cable –BNL-N-4-0010

Arup K. Ghosh
Brookhaven National Laboratory

Abstract

This report catalogues the preparation and testing of 1.5m samples of 30-strand Rutherford Nb_3Sn cable made from strand with J_c ~ 2000 A/mm^2 at 12T. Samples of this cable were heat-treated in a straight form, vacuum impregnated with epoxy and tested in a background field of 7T. Even after 40 quenches, no voltage onset was detected at a current of ~ 15,200 A. The expected critical current from strand measurements is ~ 20 kA at this background field. Results of quench velocity measurements are also reported.

Introduction

The testing of short samples of Nb_3Sn cable has been a difficult task as the nature of this superconductor renders the cable susceptible to critical current degradation due to improper handling and mechanical stresses. Initial tests of ITER-strand cable showed that the critical currents of epoxy-filled fiber-glass insulated cables could be measured at fields of 5 to 7T. In most cases the V-I curve could only be observed for one of the two cable samples, that which had a slightly lower I_c. ITER-cables typically have a high RRR and do not exhibit much training. In contrast, the high Jc cables have been harder to test than the ITER cables. To reduce the effect of non-uniform compressive stress (seen in some previous tests), the samples are vacuum-impregnated with epoxy in a newly designed fixture that ensures that the composite dimensions are well controlled.

Sample Details

Table 1

Cable ID	Length	Comments	Cu/non-Cu
	Feet		
BNL-N-3-0010	38	30-strand Inner	0.85
BNL-N-3-0011	204	30-strand Inner	0.85
BNL-N-3-0012	214	30-strand Inner	0.85
BNL-N-3-0013	206	30-strand Inner	0.85
BNL-N-4-0010	61	30-strand outer	1.5
BNL-N-4-0011	221	29-strand Cable	1.5
BNL-N-4-0012	433	30-strand outer	1.5

30-strand inner-grade and outer-grade cables were fabricated at NEEWC from strand (J_c ~ 2000A/mm^2 at 12T) manufactured by OST. These cables are to be used in the construction of a 12T common-coil dipole magnet. Table 1 lists the different lengths of cable that were manufactured. For this test, two 1.5m long pieces of the spool BNL-N-4-0010 were used. These pieces were first vacuum-impregnated with Mobil 1 and then were reacted in vacuum using the following heat-treat (HT) schedule: 100 hrs @210C, 48 hrs @340C, and 150 hrs @650C. (Note that this differs slightly from OST HT-schedule of 180 hrs @650C.) These samples were reacted in a straight configuration so that *no bending strain* is introduced when tested in the short sample holder. In future samples will be taken from lengths heat-treated on a reaction spool.

Following the HT, the sample ends were solder filled ~ 15 cm at the return end and ~ 30 cm at the lead end. The return joint ~ 15 cm long was made using a solder fixture. Samples were then vacuum-impregnated with CDT101 epoxy in the configuration shown below. The composite dimensions after impregnation were within +/- 0.001".

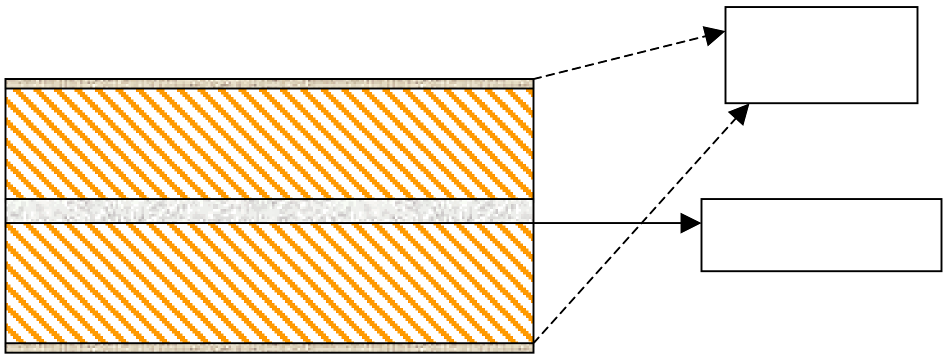

Figure 1 Cross-section of the cable sample arrangement in the epoxy fixture

The electrical insulation is similar to what is being used for the 10-turn coil fabrication. This sample composite was mounted in the standard short-sample test holder. In a prior test of an ITER-cable composite, the uniformity of the compression applied by the test fixture was verified by using Fuji-paper. The first test was done at a pre-compression of 35 MPa (5kPSI).

Voltage taps were soldered to the wire at the edge of the cable as shown below. However, these may not measure the voltage across the width of the cable if the contact resistance is very high between the strands, which are very likely. Taps were also soldered at the ends of the cable which were initially filled with solder.

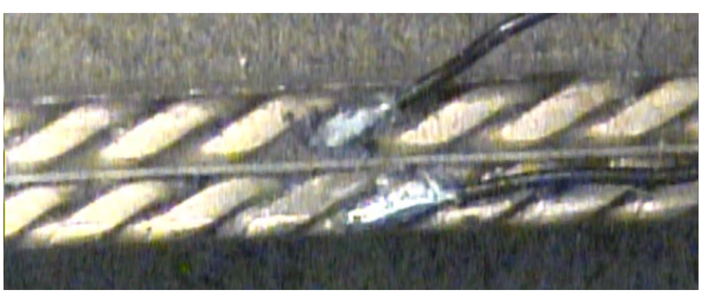

Figure 2 Edge view of the cable showing the location of the voltage taps.

The test was made in a field of 7T, with the field applied parallel to the wide face of the cable. The current polarity was such that the self-field adds to the applied field. The peak self-field is calculated to be 0.09 T/ kA.

Experimental Results

1. Quench Behavior

Figure 1 is a plot of the quench current observed. In all cases the quench origin was in the sample within the holder and not in the leads.

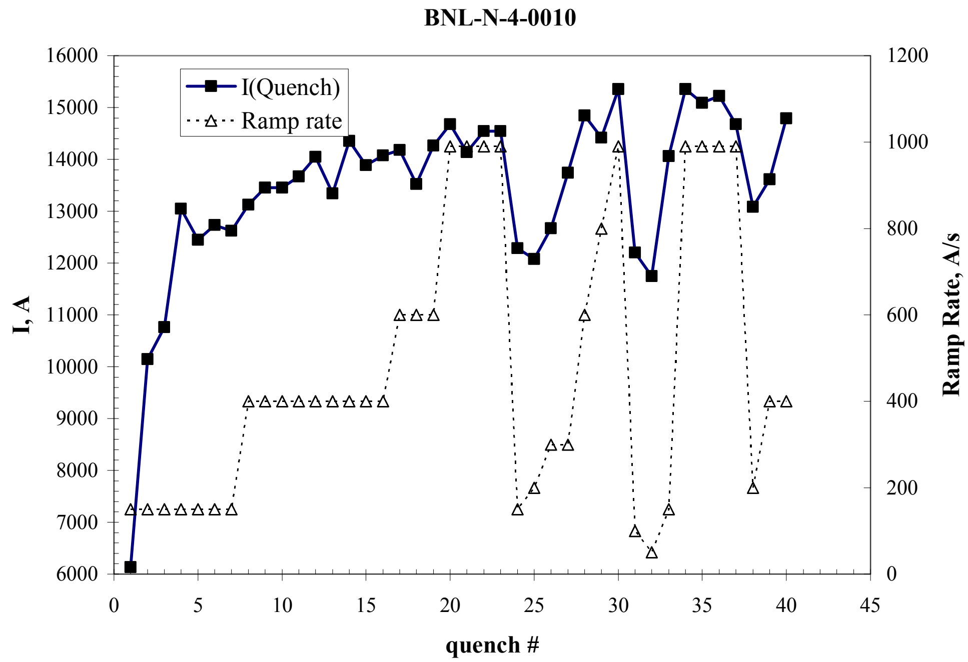

Figure 3. Quench plot. Ramp rate used is shown also.

In this figure the current ramp rate is also shown. Although, the quench behaviour is somewhat erratic, there seems to be a ramp-rate dependence which is shown in Figure 2.

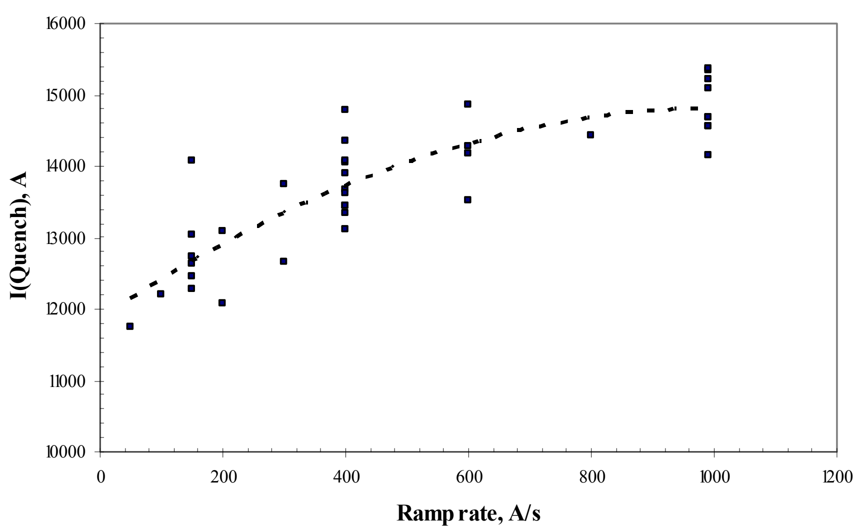

Figure 4. Quench Current as a function of Current Ramp Rate.

At the highest current of 15.2 kA, no voltage onset was detected. The return joint resistance was measured to be ~ 3 nΩ. Figure 3 shows the quench history when plotted along the peak-field load-line. The expected cable performance based on the strand data of OST is shown to illustrate the level at which the cable is quenching. The strand data to 8T was extrapolated from 9T. It would appear that the cable is operating at 70% of strand critical current.

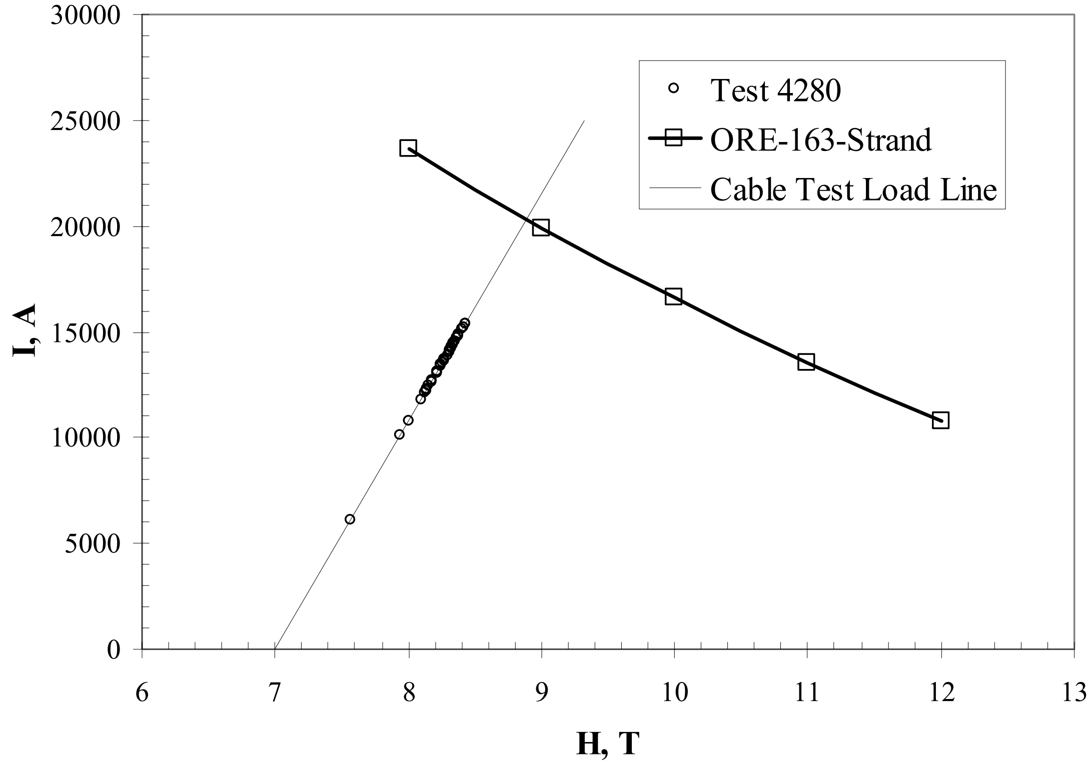

Figure 5. Quench current as a function of peak-field on the conductor, at 7T background field.

2. Quench Velocity Measurements.

For this test a spot heater (~ 10mm long) was incorporated under the top presser-bar, and was used to initiate a normal zone across the width of the upper cable. From the initial slope of the voltage rise as a function of time, a velocity of quench propagation was calculated. In addition the transit time for quench to propagate across the insulation to the lower cable was also measured. The normal-state resistance Ro at ~ 18 K (which is the T_c of Nb_3Sn) was measured to be 3.2 μΩ/cm (RRR calculated ~ 8). Figure 4 is a plot of this initial velocity and the transit time measured for different current settings with the background field of 7T. The quench velocity is surprisingly very high and at 14kA are over 250 m/s. The rapid increase in this velocity at 14 kA would imply that the conductor is close to its stable operation under the cooling conditions of the test.

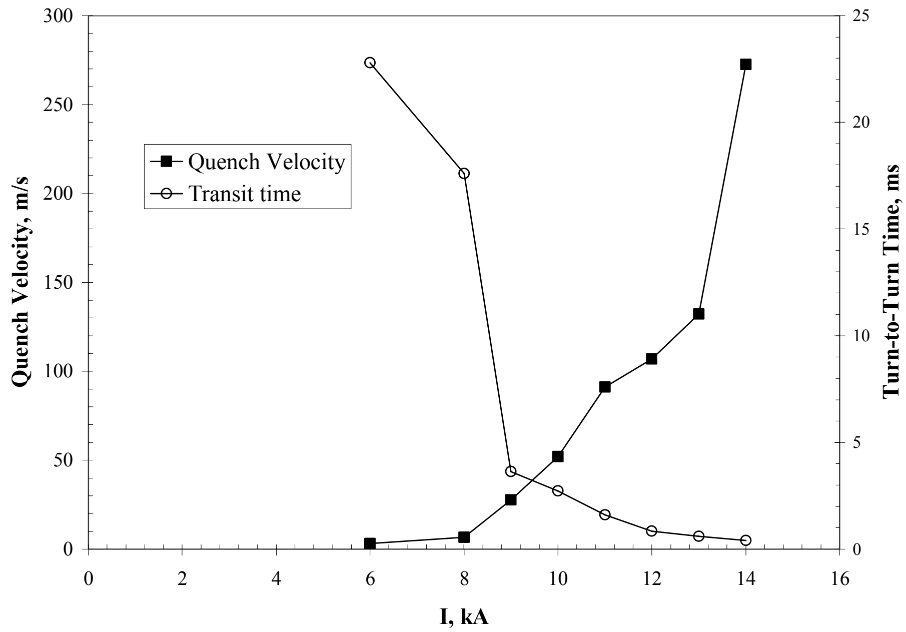

Figure 6. Initial Velocity of Quench Propagation and the turn-to-turn transit time.

Summary

Based on strand data it would appear that the conductor is operating well below its potential. It is possible that the conductor is still training, or that the cable is quenching due to transient motion of the strands. Below is a micrograph of the cable sample cross-section. Two such sections were polished and examined. It would appear that there are voids within the cable (highlighted by the dye-penetrant), but not between the cables. Could this be the source of transient disturbances that produces a pre-mature quench?

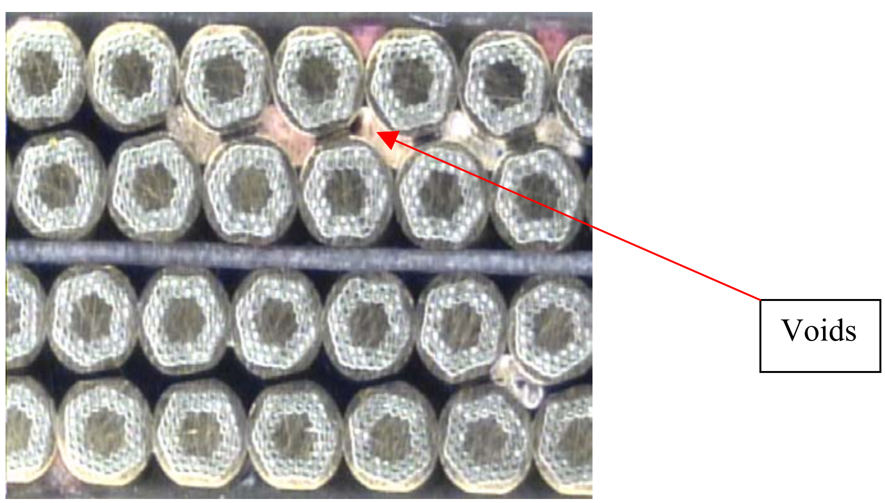

Figure 7 Cross-section of the samples. Occasional voids within the cable, none between the cables.

Also notice that there is quite a gap within the cable as the composite was not compressed during the impregnation process. This needs to be examined for future epoxy-impregnations.
The ramp rate effect observed whereby the current is higher with higher ramp rates would seem to suggest that current imbalance between the strands maybe taking place. If so then the strand with a higher current than the average would initiate a quench when it reaches its Ic. In these samples which have an oxide coating on the strand (this prevents sintering) due to Mobil 1 and the use of vacuum-impregnation of epoxy would make current-sharing almost impossible between the strands. The high quench velocity would also tend to imply that the conductor is at its critical surface.
To test this hypothesis additional tests on this cable are planned to check the reproducibility of the data and to fabricate samples where current-sharing can be re-introduced by solder filling the cable. Also as a further check on the HT, strands samples would be heat-treated on a ITER-style reaction barrel along with the cables and measured separately in the 12T solenoid magnet.